

Enhancing Energy Sector Resilience: Integrating Security by Design Principles*

Dov Shirtz¹, Inna Koberman^{1,2}, Aviad Elyashar^{2,3}, Rami Puzis^{1,2} and Yuval Elovici^{1,2}

- 1 Cyber@BGU, Cyber Labs at Ben-Gurion University
- 2 Department of Software and Information Systems Engineering, Ben-Gurion University, Israel
- 3 Department of Computer Science, Shamoon College of Engineering, Beer-Sheva, Israel

Abstract

Security by design (SbD) is a concept for developing and maintaining systems that are, to the greatest extent possible, free from security vulnerabilities and impervious to security attacks. In addition to technical aspects, such as how to develop a robust Industrial control system (ICS), hardware (HW), software (SW), firmware, communication product, etc., SbD also includes soft aspects, such as organizational management's attitude and behavior, and employee awareness.

Under the SbD concept, systems, i.e., in our context ICS, will be considered more trustworthy by users; users' trust in the systems will be derived from meticulous adherence to SbD processes and policies. In accordance with the SbD concept, security is considered. Security measures are implemented, at every stage of the product and system development lifecycle, rather than afterward, which is beneficial, enabling the identification of vulnerabilities early in the development process; when vulnerabilities are identified at an early stage, the ability to address them is improved, and the cost of resolving them is reduced, saving time, money, and effort.

As mentioned above, the SbD approach focuses on making systems as secure and immune to attack as possible through the use of measures such as continuous testing, authentication, safeguards, and adherence to best programming practices. As such, SbD enables an organization to formalize the design of its infrastructure and applications and build and integrate security into its IT and OT processes.

* Supported by the U.S.-Israel Energy Centre managed by the Israel-U.S. Binational Industrial Research and Development (BIRD) Foundation

This document presents the security requirements for the implementation of SbD in industrial control systems. The information presented does not negate any existing security and cyber security standards, quality assurance standards, best practices, or management methods such as COBIT. Instead, we strongly recommend that organizations should implement and comply with those standards and best practices.

Security by design is not a one-time process. It starts at the very beginning of a product or system’s design and continues throughout its lifecycle.

Due to the benefits of SbD, higher level of security, and robustness to cyber-attacks, all organizations associated with the energy sector should strive to establish an ecosystem. Such an ecosystem, that will be guided by SbD will contribute to a higher level and improve the overall cyber security of its participants.

This ecosystem should include each energy organization, its business partners, the hardware and software manufacturers, integrators, etc.

The requirements presented in this document may be perceived as burdensome by organizations; however, strict compliance with the requirements and existing security standards and best practices, including continuous monitoring, as specified in this document, is essential to realize an ecosystem-driven and protected by SbD.

Keywords: Security by design, energy sector, cybersecurity, Industrial control systems.

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1. Preface

In recent years, industrial control systems (ICSs) in general and those associated with the energy sector, have been the target of numerous cyber-attacks [Parachute 2022, Kessem 2021, Fox 2021]. Therefore, US Presidential Policy Directive 21 (February 2013) identified energy as critical infrastructure. It is thus imperative that the energy sector, which is considered a high-profile targeted industry [Parachute 2022], should adopt new and advanced methodologies, frameworks, and technologies to protect itself from cyber-attacks. As a result, the energy sector should increase its investment in cyber security to protect energy organizations and their customers from cyber attacks.

The energy sector is not monolithic, it includes industries such as power plants, electricity storage systems, and virtual electricity generators. Each industry, mentioned above, has its own operational technology (OT) infrastructure and information technology (IT) infrastructure. Nevertheless, all of these industries are considered critical infrastructure, and all of them are vulnerable to cyber attacks.

In recent years, a number of cyber criminals have managed to bypass security controls and exploit vulnerabilities in IT and OT systems, such as the attack on the Colonial Pipeline in May 2021.

Today, there are many standards, methodologies, frameworks, and best practices (BPs) aimed at improving cyber security, and there is a relatively high level of cyber security protection in general. Despite the availability of all of these standards, methodologies, frameworks, and BPs, no coherent framework exists for their implementation in the context of SbD.

In this document, we present an SbD framework that structures and describes the requirements for establishing SbD OT and IT infrastructure. We don't aim to replace cyber security standards and BPs, but rather to use them as the foundation for establishing the concept and framework for SbD implementation.

The proposed SbD framework has the potential to contribute to the construction of products and systems with enhanced cyber security resilience and trustworthiness, i.e.,

increase the ability of the organizations in the energy sector to become more resilient to cyber attacks, thus improving their trustworthiness.

The implementation of the SbD framework requires a paradigm shift from availability to security, integrity, and availability as well as other security building blocks, e.g., nonrepudiation, access control. It is therefore necessary to change the current methods of building hardware (HW) and software (SW) products and systems related to the energy sector, from solely focusing on availability to also focusing on security and integrity – and the adoption of an approach in which all other building blocks are equally as important as availability.

This shift can be interpreted as considering and implementing all aspects of security to the development and maintenance processes of any HW, SW, and system lifecycle, including requirement setting, design, testing, manufacturing, and the integration of these products into the organization's production infrastructure. This may influence the development and selection of OT, IT, security, and security remediation products.

SbD is an organizational state of mind. Because this state of mind needs to be adopted across the entire organization, with implications on behavior and actions, we consider two elements. The first focuses on managerial and management-related issues, while the second focuses on technical aspects. As such, the suggested SbD framework has two components.

The first component pertains to the responsibilities of the organization's top management and directorate down to those of each employee. It also includes all business partners, manufacturers of HW, SW, systems, etc. Therefore, the organizations related to the energy sector should establish an ecosystem that includes all energy companies, manufacturers of the artifacts used by the companies, and business partners.

The second component pertains to the technical requirements of SbD framework and is presented to all participants in the ecosystem. It provides a detailed description of the requirements for implementing SbD infrastructure. Moreover, it establishes a foundation for the implementation of modern cyber security mechanisms such as moving target

defense (MTD), zero trust, and blockchain. The requirements are presented according to the lifecycle of HW, SW, and systems.

It should be noted that the SbD framework is not intended to replace international standards, frameworks, and BPs but rather to build on them, and the physical sites of organizations in the energy sector are assumed to be highly secure. We do not address physical security requirements. In addition, the SbD framework continuously evolves in response to technology changes, new threats, etc.

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1.1 The Purdue Model

The Purdue model is used as a reference model in this document [Williams 1994]. The Purdue model divides an ICS into six levels (Fig. 01).

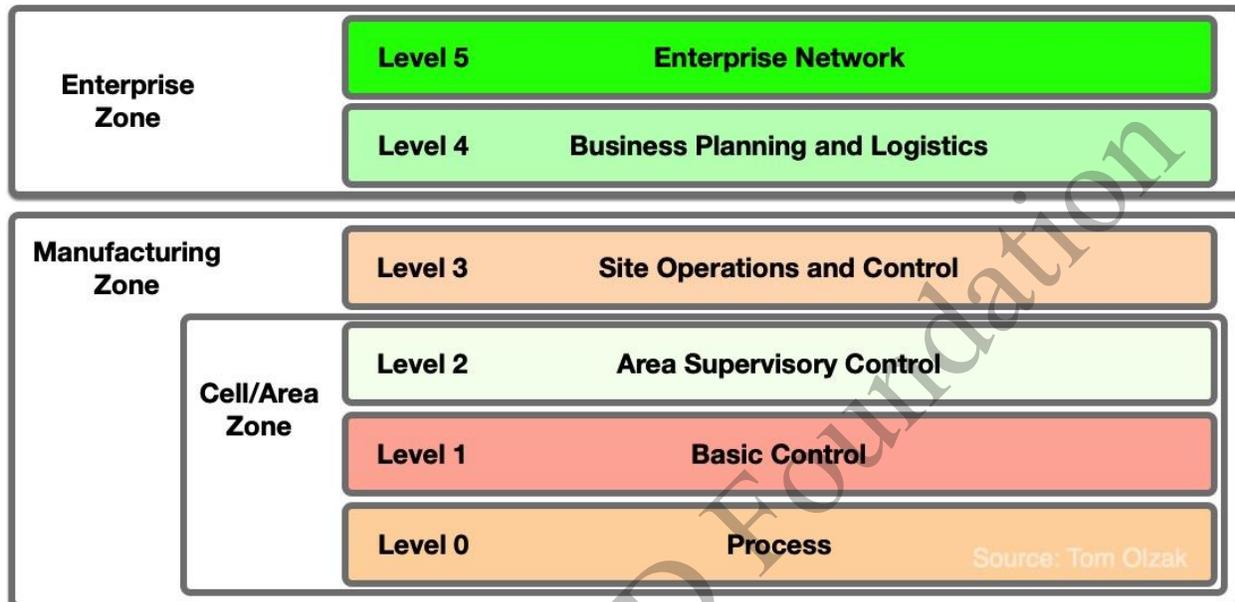


Figure 01: Purdue model schema (taken from [Olzak 2021]).

- Level 0 contains physical devices, e.g., sensors, IoT devices, IIoT devices.
- Level 1 contains components that interact with the physical devices located in level 0, e.g., programmable logic controller (PLC).
- Devices in level 2 interact with components located in level 1. In most cases, these interactions are automated, but human operators can also interact with devices via human-machine interfaces (HMIs).
- In level 3, the operational area or zone is defined as the area that controls operations in levels 0-2. The systems in this level collect and manage information from across an entire geographical area.
- In level 4, information from previous levels is provided for business system functionality supporting production, e.g., logistics. IT components in this level include servers, applications, database servers, etc.

- Level 5 contains the organization's IT network with all its functions, e.g., HR, CRM, finance.

It is important to note the following:

1. The commercial off-the-shelf (COTS) market is filled with a wide array of products used in levels 0-2.
2. The communication between levels 0-3 is based on protocols, such as Modbus, Distributed Network Protocol 3 (DNP3), and communication technologies, such as 5G.
3. A level 0 device may be analog or digital, but all devices at this level must employ some form of communication method and protocol in order to communicate with devices, components, or systems at higher levels.
4. Levels 0-3 define the OT part of the ICS, and levels 4-5 define the IT part of the ICS. For security reasons, there is a demilitarized zone (DMZ) between these two parts. A DMZ is also needed between levels 2 and 3. Usually, it is advisable to have a firewall between these two DMZs.

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2. Preliminaries

2.1 Objective

In this document, we aim to:

1. Establish an SbD framework for the energy sector to achieve the goal of SbD.
2. Promote compliance with international security standards, frameworks, and BPs.
3. Incorporate quality assurance international standards, frameworks, and BPs into the SbD concept.
4. To achieve the goal of SbD, the energy sector must:
 - a. Establish a cyber security ecosystem (Fig. 02) that includes manufacturers of HW and SW used by the energy sector, systems integrators, business partners, and service suppliers such as Internet providers, as well as all organizations within the energy sector.
 - b. Establish the following entities, which will be part of the cyber security ecosystem:
 - A computer emergency response team (CERT) and a security operations center (SOC). The CERT and SOC should be at the sector level, i.e., a community CERT, and be connected to all of the ecosystem's organizations within the energy sector.
 - An education, awareness, and research center for cyber security. This center will provide high-level cyber security education and awareness programs adapted to the ecosystem's organizations, as well as promote cyber security research relating to topics of interest to the energy sector. Note that the existence of this center does not replace an organization's responsibility for promoting cyber security education and awareness internally.
 - A central institution for testing, accreditation, and certification which will be responsible for testing products, accreditation, and certification of companies associated with the energy sector. This entity will serve as a checkpoint, enabling the entrance of a wide range of products and services to the ecosystem. The existence of this institution does not replace an organization's obligation to perform on-premises tests.

- c. Establish security practices related to the design, development, acquisition, maintenance, and operation of information resources. Information resources include information from both the OT and IT environments, and both internal and external information.
- d. Ensure the integrity of OT and IT products and services by establishing infrastructure for testing and validating their security.
- e. Promote continuous cyber security risk assessment.
- f. Promote the implementation of the proposed SbD framework, particularly in organizations that did not originally build their systems with security at the forefront.

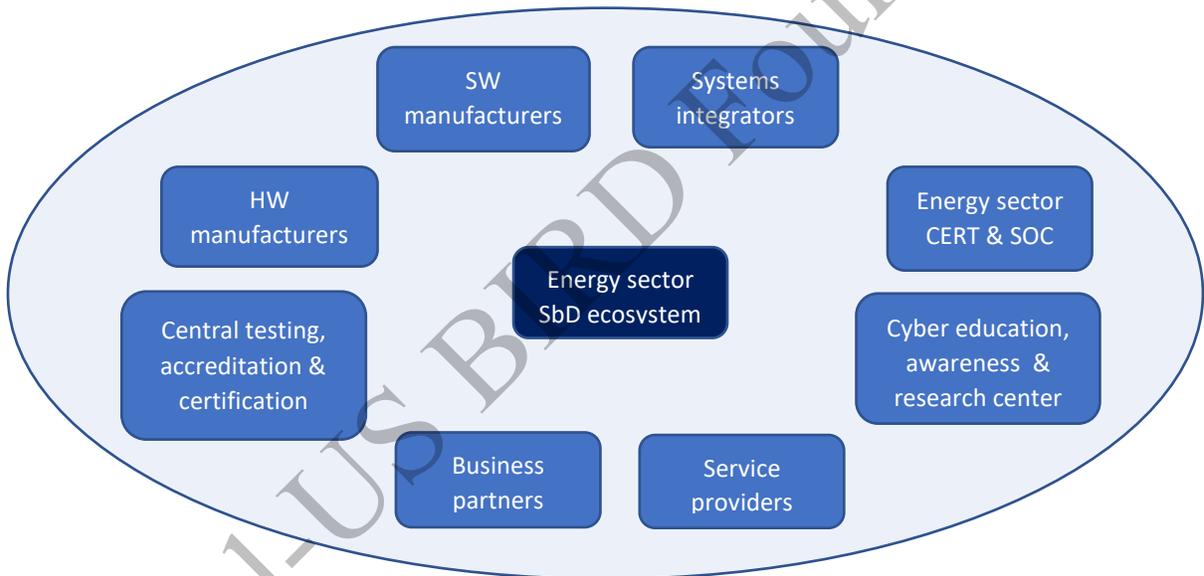


Figure 02: Entities in the Energy sector SbD ecosystem.

2.2 Applicability

This document applies to all organizations in the energy sector ecosystem.

2.3 Obligations of the Energy Sector Ecosystem's Organizations

All organizations and companies that are part of in the ecosystem (mentioned in Sections 2.1 and shown in Fig. 02 are required to do the following:

1. Comply with the proposed framework.
2. Prioritize cyber security and take all necessary steps to protect and manage their systems and data.
3. Maintain good standing, i.e., obtain and maintain certification in accordance with all international standards, implement frameworks, and uphold BPs and comply with state laws pertaining to cyber security.
4. Continuously improve their cyber and information security capabilities, policies, and procedures.
5. Strengthen the organization's resilience to operation disruptions caused by cyber attacks.
6. Continuously assess IT, OT, cyber, and information security risks, from a systemic, organization-wide perspective, within the frameworks of the regulations, directives, and standards to which the organization must adhere.
7. Continuously assess, document, and address cyber and information security risks relevant to the organization's operations, and implement mitigation measures.
8. Explore and address cyber and information security scenarios that could affect its activities and those of its customers, suppliers, and service providers.
9. Explore the scope of potential cyber and information security threats, as well as the security capabilities required to combat them.
10. Ensure that the methodology for managing and handling cyber and information security events complies with relevant international standards.

Part I – SbD Non-Technological Issues

1. Governance

Energy sector organizations' board of directors and senior management will play a major role in achieving the goal of SbD across the sector and ensuring its sustainability across the ecosystem.

There are two situations in which SbD should be implemented. The first is when creating a new product or service or when making a change to an existing ICS system. In such cases, SbD should be implemented from the beginning. The second situation is when the organization integrates SbD in an existing ICS environment.

In both cases, the SbD process should be led by the board of directors and senior management. This process begins with the board and senior management's embracing of cyber security, and their adoption of a cyber security mindset and implementation of cyber security methods and policies. A description of the relevant responsibilities and activities of the board, senior management, chief information security officer (CISO), and the internal IT audit function is provided in the subsections that follow.

3.1 Board of Directors

With respect to the board's responsibilities regarding SbD, we make the following assumptions:

- As part of its managerial activity, the board affirms its commitment to cyber and information security. It also sets the organization's cyber and information security risk management strategy. Given that, the board of directors lays the groundwork for the implementation of the SbD framework across the organization and influences both the behavior of the organization with respect to adoption of the framework as a whole and other organizations as well.

- The board's actions related to cyber and information security, risk management, outsourcing, backup and recovery from cyber incidents and disasters, etc., are aligned with international standards, frameworks, BPs, and state regulations.

Given those assumptions, the board is responsible for:

1. Approving the organization's SbD strategy and policies.
2. Appointing a subcommittee of the board of directors to oversee the implementation of the SbD framework in all organizational OT, IT, environments, computers, networks, systems, and maintenance projects.
3. Ensuring that all annual and interim work plans regarding cyber and information security, business continuity, and disaster recovery are aligned with the SbD framework.
4. Supporting inter-organizational collaboration in the implementation of the SbD framework.
5. Ensuring that all OT controls, IT controls, and controls at the interface between OT and IT are aligned with the SbD framework.

Note that in the absence of a board of directors, these responsibilities will be carried out by the organization's senior management.

3.2 Senior Management

With respect to senior management's responsibilities regarding SbD, we make the following assumptions:

- Like the board of directors, as part of its managerial activity, senior management affirms its commitment to cyber and information security. It also establishes the organization's cyber and information security risk management strategy. Given that, the board of directors lays the groundwork for the implementation of the SbD framework across the organization and influences both the behavior of the organization with respect to adoption of the framework as a whole and other organizations as well.

- Like the board of directors, as part of its managerial activity, senior management affirms its commitment to cyber and information security, risk management, outsourcing, backup and recovery from cyber incidents and disasters, etc., are aligned with international standards, frameworks, BPs, and state regulations.

Given those assumptions, the senior management is responsible for:

1. Creating an organizational mindset for SbD management and overseeing its implementation and ongoing maintenance.
2. Establishing the organizational SbD strategy and approving its policies.
3. Ensuring that cyber and information security policies are coordinated and aligned with the SbD framework.
4. Discussing, at least on an annual basis, whether the organizational SbD policies need to be modified.
5. Allocating the necessary resources for the implementation and ongoing maintenance of the SbD framework and policies.
6. Reviewing and discussing reports (regularly scheduled, ad-hoc, or required) provided regarding implementation of the SbD framework.
7. Reviewing and discussing monthly reports on significant cyber and information security incidents and analyzing their implications on the organization. These reports and discussions may influence the SbD framework as already mentioned in section 1.
8. Establishing an SbD steering committee headed by a member of the senior management.
9. Designating a CISO for the organization and defining his/her scope of responsibilities and areas of authority, with the expectation that he/she adopt a proactive approach to cyber and information security and SbD.
10. Promoting inter-organizational collaboration in the implementation of the SbD framework.

3.3 Internal Audits

The internal audit function is an organizational unit responsible for all audit activities within an organization.

With respect to the internal audit unit's responsibilities regarding SbD, we make the following assumptions:

- The internal audit activities include the auditing of cyber and information security, OT and IT environments, communication, risk management, outsourcing, survivability, and backup and recovery from cyber incidents and disasters, etc.
- The internal audit unit activities are aligned with international audit standards, frameworks, BPs, and state regulations.

Given those assumptions, the internal audit is responsible for:

1. Auditing the processes associated with the implementation and maintenance of the SbD framework.
2. Ensuring that the unit receives training to improve its capabilities and performance; The organization's senior management should allocate the necessary resources to perform auditing processes and ensure that adequate training is provided to the unit.
3. Auditing, at least annually, all aspects pertaining to SbD, i.e., the comprehensive audit should review the organization's survivability, backup, and recovery processes, etc. related to the SbD framework.
4. Reporting the findings of the SbD audit findings to the senior management and board of directors who will discuss the findings of the audit as stated in the previous subsection.

3.4 The Chief Information Security Officer

The appointment of a chief information security officer (CISO) and the definition of the responsibilities of this position, particularly in relation to SbD, and its place in the organizational hierarchy are assumed to have been performed by senior management (as

mentioned in Section 3.2) in accordance with international standards, frameworks, BPs, and state regulations.

Given those assumptions, the CISO is responsible for:

1. Advising the board and senior management on cyber and information security management in the OT and IT environments, and the necessary actions for fulfilling the requirements of the SbD framework.
2. Establishing and formulating the methodology, policies, and procedures required to implement the SbD framework in the organization. The SbD methodology and policies should be approved by the board and senior management (as stated in Sections 3.1 and 3.2).
3. Coordinating and integrating all organizational efforts related to the implementation of the SbD framework. And responsible for ensuring that the SbD framework, policies, and procedures are properly implemented.
4. Ensuring an ongoing process of assessing cyber and information security risks by the relevant organizational units in order to assess the impact of their activities on the implementation of the SbD framework, if any.
5. Establishing reporting procedures, in order to ensure that the relevant organizational units submit ongoing and ad-hoc reports about the implementation of the SbD framework and reviewing those reports.
6. Evaluating the effectiveness of the SbD framework's implementation in cyber and information security readiness exercises, e.g., internal exercises, exercises with business partners, etc.
7. Enhancing organizational awareness regarding the concept of SbD and the activities required for its implementation.
8. Analyzing cyber and information security related incidents occurring worldwide and assessing their potential impact on the organization, including SbD framework's implementation, and implementing any necessary measures.
9. Reviewing and assessing the security controls in the organization on a regular and ad-hoc basis.

10. Preparing and submitting annual reports that cover activities related to SbD framework, to the board and senior management, describe the organization's cyber and information security defense level, weaknesses and vulnerabilities, available countermeasures, and the activities and budgets required to enhance organizational defenses.
11. Collaborating with relevant institutions involved in SbD issues.

3.4.1 Appointment

1. The CISO will be appointed by senior management and tasked with specific responsibilities, duties, and organizational authority.
2. The CISO should possess appropriate education, skills, and experience in the fields of cyber and information security for both OT and IT environments.
3. The CISO will serve as the decision-maker in cases in which there are conflicts, misunderstandings, disagreements, etc., regarding the organization's obligation to fulfill the SbD framework's requirements.
4. The CISO should not hold any other position or have other responsibilities within the organization, as this could impact his/her role as CISO.
5. The organization's senior management will provide the CISO with all of the resources needed to fulfill his/her responsibilities.

3.4.2 CISO's place within the Organizational Hierarchy

1. The CISO will be directly supervised by a member of the senior management.
2. The CISO will have autonomy in selecting the required work and reporting interfaces between himself and other officials within the organization or with other organizations. These interfaces should be approved by senior management.

4. Part II SbD – Technological Issues

In the subsections that follow, the technical requirements for the implementation of the SbD framework are discussed.

4.2 Standards, Best Practices, and Accreditation

This section presents standards, frameworks, and BPs related to ICS security, IT security, and quality assurance. In addition to adopting the standards, frameworks, and BPs listed below, each organization in the energy sector's ecosystem should fulfill the following requirements:

1. The organization should be appropriately accredited. Accreditation is crucial, since it establishes some basis for the level of security of the organization.
2. The accreditation should be renewed annually or in accordance with the requirements of the accrediting institution issuing the standard or BP.
3. If there is no formal accreditation process associated with a standard or a BP, an accreditation-like process should be conducted by an external expert in the subject matter. The results of the accreditation processes should be presented to the board and senior management.
4. The expectation that all organizations in the ecosystem will be appropriately accredited does not exempt an organization from performing its own on-premises tests for COTS and services provided by accredited third-party services.

4.2.1 List of Standards, Best Practices, and frameworks

1. Organizations and suppliers should be certificated with respect to the following standards and BPs. Certification should always be in accordance with the latest version of a standard or in accordance with the new standard in cases in which an old standard has been replaced. For standards without certification or accreditation processes, please refer to section 4.2 clause 3.
2. Organizations in the ecosystem should adhere to the following standards and BPs:

- a. General security standards
 - ISO27k - Security standards.
 - NIST CSF - NIST Cyber security framework.
 - NIST SP 800-53 Risk management framework.
 - NIST SP 800-171 Protecting controlled unclassified information (CUI) in nonfederal systems and organizations.
 - b. Industrial control system standards
 - NIST SP 800-82 - Security management of cyber-physical control systems
 - ISA/IEC 62443 - Industrial automation and control system security series of standards.
 - CIS - Critical security controls.
 - c. SDLC standards
 - ISO/IEC 12207 - Software life cycle processes
 - NIST 800-218
 - d. Quality assurance and quality control standards
 - ISO/IEC 25K - SQuaRE (System and Software Quality Requirements and Evaluation) standard
 - ISO 9000 - Quality management series of standards.
 - ISO/IEC/IEEE 29119 - Software testing series of standards.
 - e. Related standards
 - ISO/IEC 33063 – Process assessment model.
 - ISO/IEC 20246 - Work product reviews.
3. The MITRE ATT&CK knowledge base (KB) should be used for specific security requirements.

4.3 Asset Management

This section describes the organization's responsibility for its OT and IT assets. An "asset" is defined as any data or information, hardware, software, communications equipment, process, policies, and procedures, etc. used by the organization. Proper asset

management contributes to organization cyber security in aspects such as: visibility, risk analysis and risk management, patch management, event handling, etc., all are building blocks of SbD.

4.3.1 Inventory

1. The organization must document its assets, build an inventory of them, and maintain an up-to-date record of them in an asset inventory.
2. The asset inventory should be computerized.
3. At a minimum, the asset inventory should include the following assets:
 - a. Tangible assets (e.g., hardware components) and intangible assets (e.g., software) located on the organization's premises.
 - b. Tangible and intangible assets that are not located on the organization's premises but are under its responsibility.
 - c. Tangible and intangible assets that are not directly under the organization's control, which when in short supply or malfunctioning could negatively affect the organization. For example, a shortage of third-party cyber security experts could delay security testing, which could prevent the timely implementation of an OT and IT product or service.

4.3.2 Ownership

1. Each asset should have a designated owner.
2. The owners of assets are the managers of organizational units within the organization.
3. The owners are responsible for activities such as:
 - a. The asset's daily use.
 - b. Ensuring that the asset is properly maintained.
 - c. Ensuring compliance with the organization's policies and procedures regarding the asset's maintenance, development, backup, recovery, and disposal.
 - d. All other cyber-security-related activities should be under the direct guidance and supervision of the CISO and his/her staff.

4.3.3 Acceptable Use

1. The acceptable use of an asset is defined as its utilization solely for the purposes of work assignments.
2. Assets that are assigned to users or organizational units can only be used for their work assignments, subject to their roles and authorizations.
3. A user should not disrupt or harm an asset.

4.3.4 Asset Mapping and Classification

1. Every asset should be assigned a unique identification number.
2. At a minimum, the asset inventory should include the following information for each asset:
 - a. The meta-data, which describes the asset (e.g., unique identification number, physical location, owner, etc.).
 - b. A mapping of the logical relations, a mapping of the physical connections, dependencies between assets, processes using the asset, dependencies such as an asset that cannot be used during maintenance activity, an asset that can be used when another asset is being maintained, etc.
 - c. Asset sensitivity, usage restrictions (e.g., cannot be used during holidays, no restrictions whatsoever, etc.).
 - d. Cyber security measures in place to protect the asset.
3. At a minimum, each item in the asset inventory should be assessed in terms of its:
 - a. Business importance, i.e., the asset's value to the organization.
 - b. Significance in OT or IT environment, e.g., the processes that will be affected in a case of a failure, etc.
 - c. Susceptibility to cyber threats.
 - d. Potential legal issues that might arise if the asset is compromised, tampered with, destroyed, etc.

- e. The potential damage caused to the organization if the asset is compromised, tampered with, destroyed, etc.
5. The asset inventory and its contents should be continuously updated.
6. The categories by which assets are classified in the asset inventory should be reviewed annually and when changes are made in the OT and IT environments.

4.4 Security Infrastructure Requirements

This section presents the fundamental cyber security infrastructure requirements associated with SbD.

1. Cyber security systems, measures, and safeguards should be determined based on risk assessment and analysis, the sensitivity of the asset, loss prediction, applicable laws and regulations, and applicable standards and BPs.
2. Cyber security systems, measures, and safeguards should be continuously updated to the highest level possible in order to properly address the issues mentioned in clause (1) above.
3. Cyber security systems, measures, and safeguards should be designed, built, and implemented with “fault-tolerant,” “fail-secure,” “self-healing,” and “self-recovery” capabilities.
4. In order to identify malicious activities and support forensic investigations, full visibility of all systems, activities, and data should be supported.
5. The implementation, development, and maintenance of cyber security systems, measures, and safeguards should not endanger or harm the capabilities described in clause (3) above.
6. An attempt to modify, distort, tamper with, or perform any other activity that was not considered by the system’s designers when designing the cyber security system, measure, or safeguard should trigger an alert in the central security incident and event management/security operations center (SIEM/SOC) as soon as it is detected. Regardless of whether the activity causing the alert is performed by an authorized or

unauthorized entity, e.g., employee, software application, or attacker, the alert should be raised.

7. The organization's senior management should ensure that its cyber and information security safeguards are certified, comply with relevant laws, regulations, standards, and BPs.
8. Outsourced activities and services (e.g., Internet services, code writing, and cloud services) should comply with the organizational security policies and procedures to ensure that the highest possible level of security is maintained. This means ensuring that the organization is protected from unauthorized access, theft, and loss.
9. Full visibility should be supported for in-house OT, IT, and outsourced activities (e.g., cloud services).
10. Cyber security issues should be coordinated with the organizational units responsible for OT, and IT, development, and operations.
11. The organization should implement and manage security safeguards for its OT, IT, data resources, and communication, including but not limited to those described in the following subsections.

4.4.1 Access Controls

1. A mechanism for identification and authentication should be in place to enable access to the organization's OT and IT environments, including production environments, test environments, development environments, etc.
2. Multi-factor authentication (MFA) (such as a fingerprint and a strong password) should be required to access the environments mentioned in clause (1).
3. A mechanism for identification and authentication should be in place to access the HW component.
4. Dynamic access control. A ZT mechanism should be implemented in the OT and IT environments and in between them.
 - a. Access to organizational assets should be granted with respect to internal and external attributes.

Internal attributes such as: IP address, physical location of the device requesting access (e.g., on premises, in a cloud environment, at an employee's home), type of device (e.g., laptop, smartphone, PLC, server), communication method, firmware version, information regarding Trusted Platform Module (TPM), etc.

External attributes such as: indicators that the organization is currently under attack, vulnerabilities that have been published and have relevance to the organization, etc.

4.4.2 Remote Access Controls

The purpose of remote access is to provide employees and external companies with access to the organization's OT and IT environments for maintenance, inquiries, and repair activities. There are two types of remote access.

The first type involves remote access required for ongoing operations, such as monitoring a remote gas pipeline.

The second type involves remote access required to handle failure or perform repairs. For example, a malfunctioning SW or HW component may require the manufacturer to investigate it remotely.

1. In general, remote access to organizational resources should be avoided as much as possible. However, when remote access is unavoidable, it should be performed in a controlled and restricted manner.
2. A clear set of criteria and procedures should be established to explain when, how, by whom, and for how long remote access may be used.
3. Remote access to the organizational resources, e.g., OT and IT environments, should be implemented using a technology that meets, at a minimum, the following requirements:
 - a. A specific and dedicated IT component, i.e., a gateway, that possesses at least the following security related capabilities, should be used to provide remote access to the organizational assets:

- Authenticate the remote user.
 - Provide support for continuous authentication.
 - All communications to and from the remote site should be routed through the component.
 - Communication between the remote site and the local site should be encrypted.
 - A detailed audit log collecting all the communication data should be maintained.
- b. The organization should have two different gateways: one for internal operational requirements and another that supports external requirements.
 - c. The organization should use technological measures, (e.g., continuous identification and authentication of the communication endpoints) To ensure and validate the communication endpoints.
 - d. The organization should use dedicated demilitarized zones (DMZs) for each gateway.
4. Requirements for internal operational remote access, i.e., first type of remote access described above (remote access required for ongoing operations).
 - a. The gateway for internal operations should be operational and powered on.
 - b. Traffic should be logged into a dedicated audit log file.
 - c. Traffic should be analyzed for potential malicious code or activity in real time.
 - d. Callers should be identified and authenticated using a secondary communication channel, in order to initiate the remote session.
 - e. There should be strong MFA (at least 2FA), e.g., a user code and a token that generates random passwords. A certificate mechanism should be used when a HW component requires access.
 5. Requirements for external remote access, i.e., second type of remote access described above (remote access required for failure or repair operations done by an external entity).

- a. The gateway for external remote access is shut down and powered off, by default. It should only be powered on and connected to the network when remote access is required.
- b. Traffic should be logged into a dedicated audit log file.
- c. Traffic should be analyzed for potential malicious code or activity in real time.
- d. The remote session should be initiated by the organization.
- e. Callers should be identified and authenticated using a secondary communication channel, in order to initiate the remote session. Initiation of sessions between the external entity and the organization should be performed manually.
- f. The remote session should be terminated manually or after its predetermined time limit has expired, whichever occurs first.
- g. Access should be protected by strong MFA (at least 2FA), e.g., a user code and a one-time password (OTP).
- h. During the session, a parallel communication channel, such as Zoom, should be used.

4.4.3 Encryption

The SbD encryption requirements are as follows.

1. Cryptography algorithms and key management must comply with either FIPS 140-2 standard or a similar up-to-date international standard or a standard in another document superseding the encryption standard in use.
2. Organizations should use the maximum key length permitted by the cryptography algorithms, e.g., encryption, digital signatures.
3. The encryption should be performed using the most secure encryption schema.
4. Regulations or state laws may stipulate a specific encryption scheme, e.g., AES with a key length of only 128 bits; in such a case, the organization must follow the stipulated encryption scheme using the longest possible key length.
5. The organization should use digital signature algorithms that are recognized as international standards.

6. Encryption and authentication keys should be exchanged according to established international standards and protocols.
7. The encryption keys should be generated and stored in a manner that prevents theft, loss, leakage, or any other risks from occurring anywhere they are stored. Encryption keys should be stored in accordance with international standards such as FIPS 140-2 or the most recent equivalent.
8. Various devices, such as firewalls, routers, PCs, servers, PLCs, IoT devices that serve as PLCs, etc., should support the following at a minimum:
 - a. The use of symmetric encryption, such as AES, DES, or the equivalent.
 - b. The use of asymmetric encryption, such as RSA, ECC, or the equivalent.

4.4.4 Certificate Mechanisms

The SbD requirements regarding certificate mechanisms and the certificates issued by certificate authorities, such as RSA, are presented below.

1. A certificate mechanism should support the highest level of certification known to date.
2. HW and SW manufactures should be able to support certificates.
3. Certification should be required for HW components, SW, applications, and users.
4. Both man-to-machine connections and machine-to-machine connections should validate the certificate before a connection is established.
5. A non-certificated HW component, SW component, application, or user should not be allowed to connect to and operate within the organization's OT and IT environments.
6. Certificates should be continuously checked and validated during operation time.
7. Certificates should only be issued by recognized certificate authorities, e.g., RSA.

4.4.3 Date and Time Synchronization

Time synchronization helps correlate log files between devices. This helps track security breaches, components issues, and network usage.

1. All digital equipment, including IoT and IIoT devices, routers, PCs, and PLCs, should be synchronized with the current date and time.
2. There should be millisecond precision in time synchronization.

4.4.4 Audit Logs

For proper audit log implementation, organizations should follow NIST special publication 800-92 “Guide to Computer Security Log Management.” This section presents SbD audit log requirements that are important to SbD.

1. Log files should be robust and protected against malicious attacks, data manipulation, and deletion by unauthorized entities, e.g., individuals, parties, or erroneous activities.
2. In order to maintain the integrity of the log recording mechanism, it should be protected against manipulation, subversion, and bypassing.
3. Administrators should not be able to modify, subvert, delete, or bypass log records.
4. Audit logs should document all system events, such as logons, logoffs, identifications and authentications, access to assets, and activities performed on assets, as well as system responses, including success and failure return codes.
5. The records of local logs stored within a device (i.e., local logs) should be transmitted to a central log. Data transmission (i.e., log records) should be protected against malicious attacks, data manipulation, and data deletion by unauthorized parties.
6. Log information should, at a minimum, consist of the following:
 - a. Date and time to the millisecond,
 - b. Identification of the transaction, event, etc.
 - c. Identification of the HW component, SW components, communication addresses, user, etc.
 - d. Address of the source and target. It should be noted that this implies that the address and identification are unique within the organization.
 - e. Any other information relevant to the transaction, event that may facilitate forensic investigation.

7. Fields in the log should be parameterized, and the CISO should determine which fields should appear in the log record.
8. The activities of the senior administration, including the CISO, should be logged.
9. It should not be possible to manipulate, subvert, delete, or bypass the log recording mechanism.

4.4.5 Data Integrity

This section deals with the importance of supporting data integrity mechanisms. The term “data” refers to data as well as any IT and OT code in any form (e.g., source code, executable code) and in any environment, including development, testing, and production.

1. Data integrity should be enforced in all states of data, i.e., at rest, in motion, and in use.
2. Dedicated mechanisms, e.g., digital signatures, should be used for data integrity enforcement.
3. Continuous checks should be performed to ensure data integrity.
4. Any integrity deviation should be reported immediately to the SIEM/SOC.

4.4.6 non-Repudiation

This short section deals with the requirement of non-repudiation mechanism.

1. To enforce non-repudiation, dedicated means should be used, such as digital signatures that include time and date information about the transaction/event.

4.4.7 Data in Motion

This section deals with the movement of data over the network.

1. Data in motion should be encrypted and digitally signed. This includes data travel on the organization’s premises as well as data travel between the organization and the external environment.

2. The digital signature should be checked by the recipient.
3. Data in motion should be protected against malicious attacks, data manipulation, and deletion by unauthorized parties.
4. Prior to encrypting data, it should be verified to ensure their accuracy and check for malicious code. The same verification/checking process should be performed after the decryption process.
5. Data should only be transferred among predefined nodes. The transfer mechanism should support parameters including, but not limited to, data identification, direction of movement, statistics such as the number of bytes being transferred, date and time of the transfer, and allowed routes of the data movements.
6. The same requirements pertain to data files used to update firmware and software.

4.4.8 Data at Rest

This section deals with the requirements related to data at rest.

1. Data at rest should, by default, be encrypted.
2. It is up to the CISO to determine whether or not to change the requirement in clause 1. Any changes should be made following a rigorous investigation in which aspects such as the sensitivity of the data, the information lifespan, the use of the data, etc. are examined. The organization's senior management should approve those changes.
3. The organization should implement a specific mechanism for identifying and preventing damage to the data's integrity. Any integrity deviation should be reported immediately to the SIEM/SOC.

4.4.9 Data in Use

This section deals with the requirements related to data in use.

1. Data in use should be protected in memory (e.g., RAM, ROM, EPROM) as well as in the CPU cache.

2. The protection mentioned in clause 1, should include the ability to prevent unauthorized modification, distortion, or reading of the information.
3. Any unauthorized activity, as described in clause 2, should be reported to the SIEM /SOC. If such an event is identified, it is up to the CISO to determine its response.
4. In case where the data in memory is encrypted there is a need to decrypt it. Therefore, decryption of data in use should take place in a protected area, (e.g., CPU cache memory) that should be protected as stated in clause 2.

4.4.10 Physical Security

This section deals with the requirements related to physical security of the OT and IT environments.

1. Physical security should be provided at all organizational sites.
2. The term “organizational sites” includes but is not limited to buildings, offices, operational sites, IT sites, communication sites, backup sites (such as hot, warm, or cold backup sites), and sites where the organization’s data resides.
3. We assume that there is comprehensive physical security in place at all locations. Please be aware that weak physical security may impact the organization’s implementation of SbD. Note that there will be **no further discussion of this topic in this document.**

4.4.11 Maintenance

Although maintenance is an ongoing process, in the ICS environment it does not appear to be a frequently performed process, especially within the OT environment. Thus, an organization may find itself with an OT device that is susceptible to cyber attacks.

We address the maintenance process in Section 5.6.

4.4.12 Risk Assessment and Audit Activities

Cyber risk assessment and audit activities are processes of identifying, analyzing, and evaluating the risk associated with the current cybersecurity setup of the organization.

1. Risk assessment should be a continuous process. Risk assessment will be performed with respect to:
 - a. In-house organizational changes in the areas of HW, SW, communication systems, etc.
 - b. Changes that occur externally, such as changes in service providers, customers, business partners, published information about cyber attacks, vulnerabilities, and academic research.
2. The organization should continuously perform a vulnerability audit scan of all elements in its network. For example, the organization should utilize a mechanism that will scan all of its communication devices, PCs, servers, etc. for (1) vulnerabilities, (2) missing patches, (3) end-of-life, etc. The vulnerability audit scans should include all ICS environments i.e., OT and IT.
3. The organization should perform penetration tests on its IT and OT environments on a quarterly basis. Usually, these networks are large, so covering all of them quarterly may not be possible. Therefore, in such cases the entire network should be examined at least semiannually.

4.4.13 SIEM/SOC

Security Incident and Event Management (SIEM) and the security operation center (SOC) help organizations prevent data breaches, alert the organizations to potential cyber events, and respond to them.

1. Every organization should maintain a security incident and event management/security operations center (SIEM/ SOC).
2. Incident and event data should be transferred to the SIEM/SOC for analysis and recommendations and to determine how the organization should react to the event.

3. The SIEM/SOC should serve the IT and OT environments and combine information from both environments. It is possible to have two SIEM/SOCs one for each environment, however they should be combined into one overall SIEM/SOC.
4. It is highly recommended that in addition to the organization's SIEM/SOC, an industry wide SIEM/SOC be established for all members of the energy sector; this entity will combine and analyze the information from the member organizations' SIEM/SOCs.

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4.5 Architectural Elements

The objective of this document is to establish the requirements for implementing the SbD environment. In order to achieve the goal of implementing SbD in ICS, basic cyber security requirements should be met. This section presents the basic architectural security requirements for ICS and communication networks. Some of the information presented in this section has already been discussed.

1. The organization should implement a secure physical and logical architecture in order to prevent, detect, rectify, and recover from breaches to its OT, IT, and communication systems.
2. The organization should implement methods and mechanisms to prevent data breaches.
3. The organization should continuously seek to enhance the cyber security measures and policies for its systems.
4. The requirements for network security elements can be found in Section 4.6.
5. The requirements for work environments can be found in Section 5.2.
6. Authentication and authorization mechanisms should be used to enable access to the organization's network and systems. Human authentication should be based on MFA. Device authentication should be based on strong digital certifications.
7. By default, the organization should prohibit the use of portable media. In extreme cases, portable media may be used, but only after it has been checked for malicious content.
8. The organization should use anti-malware and sanitization mechanisms to prevent malicious content, such as malware, from infecting its network, systems, and servers.
9. The organization should use anti-malware and sanitization mechanisms to prevent incoming and outgoing files containing malicious content from infecting its network and external networks.
10. The organization should use encryption methods to protect its data files. Permission to inspect the data files should be given on a need-to-know basis and for audit purposes.

11. The organization should monitor its internal networks and systems, such as PCs and servers, for malicious activity and policy violations by both internal and external parties.
12. The organization should strive to implement cutting-edge technology based on anomaly detection algorithms in order to detect zero-day attacks, malware, and other malicious activities.
13. Each device should be equipped with a TPM which will be used in activities such as the boot process and controlling the memory.
14. Each device at levels 0-3 of the Purdue model should be duplicated. Ideally, this will enable proper and timely maintenance activities to be performed on level 0 to 3 devices. Please note that IT device duplication is a common practice in an online environment (e.g., internet sites).
15. A level 0 OT device should be connected to at least two level 1 OT devices. A potential benefit of this requirement is the ability to identify attacks on level 0 OT devices and take proper action.

4.6 Network

In this section, we discuss network component cyber security. Note that the organization is assumed to have implemented safeguards such as firewalls, intrusion detection and prevention systems (IDPSs), identification and access control systems, data leakage prevention (DLP) systems, and protection of wired and over-the-air communication.

4.6.1 Areas of Emphasis

In addition to the network requirements mentioned later in this section, we wish to emphasize the following:

1. The unused ports in the network switches and routers should be disabled; this can be done manually or by using a software application that controls access to network resources.

2. Communication components should be hardened to a level that is adequate, in accordance with standards and cyber security BPs.
3. The configuration of all network elements and cyber security safeguards should be backed up.

4.6.1.1 Network Management

This section deals with the requirements regarding basic network management requirements.

1. The organization should formulate a policy aimed at enhancing the cyber security of its network elements, systems, and workstations.
2. A network management system (NMS) should be used to control the OT and IT networks' components, such as routers, bridges, etc.
3. At a minimum, the NMS should have the following properties:
 - a. The NMS should be protected by safeguards that monitor and control the incoming and outgoing network traffic based on predetermined security rules (e.g., firewall, IDPS) and by behavioral mechanisms that can detect internal and external attacks, malicious activities, and policy violations.
 - b. Depending on the organization's environment, the NMS should be logically divided into different parts.
 - c. Administrators should not be permitted to manage the network from their workstations, which may have other connections, such as Internet, email, or other applications.
 - d. Administrators should use MFA to access the NMS.
4. All administrative activities within the organization should be audited and recorded in logs and sent to the SIEM/SOC.

4.6.1.2 Network Elements

This section deals with the requirements regarding basic network security settings.

1. The organization's internal networks should be segmented according to criteria related to organizational structure, functionality, information sensitivity, and risks.
2. As part of the internal network security measures should be implemented (e.g., firewalls between the segments, relay mechanisms, information filtering) in order to prevent the injection of hostile codes; proxy systems should be used to conceal the segment infrastructure from hostile actors; and measures should be implemented to identify, detect, and raise alerts regarding suspicious (1) activity, (2) data and data movement, (3) applications, and (4) access.
3. Data movement, access rules, and security rules related to internal networks should be predefined and monitored for suspicious activities. The monitored data and related activities should be logged and sent to the SIEM/SOC.
4. The organization should maintain strict separation between its internal networks and all entities located outside its premises, including the Internet, suppliers, service providers, customers, etc.
5. In order to maintain the security of its connections with external parties (e.g., customers, suppliers, business partners), the organization should implement security measures.

4.6.2 Network Data Encryption

1. As stipulated in Section 4.4.7, data in motion should be encrypted.
2. Management traffic should be encrypted.

4.7 Remote Access

This subject is dealt with in Section 4.4.2.

5.0 Security by Design for System Development

5.1 Introduction

In this section of the document, we discuss **general aspects of Sbd** requirements concerning the development or purchase of HW or SW components for the OT or IT environments.

Three types of products are considered.

- a. A product developed by the organization on its own.
- b. A product purchased by the organization.
- c. A product that is a combination of the two other types mentioned above (e.g., using API developed by the organization in a purchased application)

In this context, the term “product” (or "artifact") is used to refer to any HW, SW, combination of HW and SW, components.

In this section we **do not** propose a new lifecycle of SW development, HW development, system development, or procurement of any of these items. We present some cyber security concerns related to system development. We believe that adhering to these requirements would result in a higher level of cyber security and robustness against cyber attacks.

1. All artifacts, HW, and SW, should be certified in accordance with relevant standards, including cyber and information security standards, and quality assurance standards. Please note that this requirement applies to all artifacts, whether they were developed internally or purchased.
2. Documentation of all information concerning internally developed artifacts, such as the development lifecycle, external testing, and certification processes, should be complete and accurate.
3. The manufacturer/creator of a HW or SW artifact should provide documentation to ensure its compliance with the required standards, BPs, regulations, and testing, including security testing.

4. SW development should be carried out using modeling languages, such as the Unified Modeling Language (UML) or Systems Modeling Language (SysML), since modeling languages are capable of supporting the entire SW development lifecycle (SDLC).
5. There should be complete bidirectional traceability in the SW development process.
6. Traceability information should be documented and logged.
 - a. In the development and maintenance phases, traceability should be ensured by linking artifacts to their requirements, design, coding, testing, and documentation. This information should be highly protected.
 - b. Traceability at runtime should track every change made to a data item, log its movement between modules, APIs, systems, etc., and log all information pertaining to the change.
7. The system should support full visibility to all of its components.

5.2 Work Environments

In this section, we discuss the necessity of establishing different work environments for development, testing, and production. Some of the reasons for establishing different work environments include:

- By protecting the integrity of the production data and code, establishing different work environments improves security.
 - It prevents the development and testing teams from accidentally corrupting the code in the production environment.
 - It enables parallel development, testing and maintenance activities.
 - The development and testing environments may be viewed as a line of defense line to identify bugs and security vulnerabilities before the code is moved to production environment.
1. At a minimum, an organization should define the following work environments: development, testing, near-production, and production, i.e., operations. It is up to the organization to determine whether any other environments are necessary.
 2. Generally, all organizational environments should be isolated from the outside world, including third parties.

3. The separation of the environments should be strictly enforced.
4. There should be a high level of cyber security protection for all the environments.
5. The movement of data (such as new SW, code updates, or firmware updates) between the environments should be performed through a specific mechanism and coordinated by all participants.
6. With respect to the mechanism mentioned in clause 5:
 - a. Data that moves between two environments should be analyzed for malicious code.
 - b. An audit trail should be maintained for each data movement.
7. Development teams should not be permitted to access the production environment. However, if, in the event of a failure, such access is required, it should be handled by the development teams from the production environment. Remote access will only be allowed under specific strict measures, as stipulated in Section 4.4.2. Each access permission and act in which a development team is able to access the production environment should be accompanied by an audit trail.
8. Security tests, including penetration tests and robustness tests, should be performed on all possible attack scenarios and access paths, including the remote access path.

5.3 Lifecycle

This section contains a general description of lifecycle activities that, in our opinion, are crucial to SbD. We do not delve deeply into each aspect of the lifecycle. There are numerous books, papers, and BPs available for this purpose. Instead, we focus on lifecycle related cyber security and SbD requirements. In this context the general lifecycle consists of the following phases: requirements, design, coding or development, testing, deployment to production, maintenance and replacement, and disposal.

5.3.1 Requirement Phase

In this phase, to the extent possible, relevant aspects of security requirements should be identified as part of the risk analysis process. In terms of security, we do not distinguish between an artifact (e.g., HW, SW) developed by an organization or the purchase of such artifacts. As a result, organizations should develop a questionnaire regarding relevant

aspects of security and either develop artifacts or consider purchasing artifacts in accordance with the answers to the questionnaire.

Generally, the requirement phase includes at least the following activities:

- a. Risk assessment and analysis.
- b. Quality assurance
- c. Identification and authentication
- d. Access control
- e. Logs/historians
- f. Audits
- g. Tests
- h. Security
- i. Communication
- j. Remote access
- k. Segregation of duties
- l. Segmentation
- m. Perimeter security
- n. Backup and recovery
- o. Physical security
- p. Law and regulations

In this document, we do not discuss each of the above activities in detail. We simply examine some activities related to achieving SbD.

The requirement phase usually occurs in cycles. We begin with a high-level risk assessment and analysis. As we progress through the requirement phase, we perform a risk analysis to identify uncovered risks and security vulnerabilities.

5.3.1.1 Risk Analysis – Understanding the Risks.

It is not our aim to explain how to perform risk assessment or risk analysis in this document. We do wish to emphasize the importance of conducting risk assessment and analysis as a cornerstone in any internal development project or in the process of purchasing an external HW and SW product.

Organizations and manufacturers should perform risk assessment and analysis before starting a project (e.g., internal development or purchasing). The process will contribute to improved understanding regarding the security risks and aspects of security that should be considered before embarking on the project. Please note that in the context of this document risk assessment and risk analysis does not refer to non-security-related project risks (e.g., adherence to the timetable and budget).

The outcome of the risk assessment and analysis activity may include:

- Understanding of the risks the organization will face in relation to the artifact developed or purchased.
- An agreement between the participants (e.g., users, developers, management) regarding the security risks and mitigation activities pertaining to the artifact developed or purchased.
- A high-level map of all security requirements and threat model pertaining to the artifact developed or purchased.
- A document stating all of the security requirements.
- A repository or KB that includes all information about the security requirements, which should be updated in every stage of the development process.
- Understanding of the dependencies between various security requirements.
- Thorough understanding of the extent to which the organization is capable of handling the security requirements.
- An overview of how to validate and verify the security requirements.
- Prioritization of the security requirements.

Whenever there is a change in an artifact (HW, or SW), infrastructure, or security requirement (e.g., new regulation), a new risk assessment and analysis of the security requirements should be conducted to ensure coverage of security risks.

5.3.1.2 Quality Assurance Requirements

Quality assurance (QA) and security are about reducing risks. Several studies have found that security and QA are correlated, i.e., applications with many QA issues tend to have a larger number of security issues [Arzt 2021, Woody 2014].

Developing high-quality products (i.e., products that have a minimal number of faults, and are reliable, accurate, easy to maintain, secure, and robust to cyber attacks), whether they are HW, SW, or systems, is challenging. Users perceive such high-quality products as trustworthy, and thus they will prefer such products or systems to those that which frequently fail, are difficult to maintain and unreliable, and are not secure (e.g., prone to information leakage, easily exploitable), which are perceived as untrustworthy. Fundamentally, security is all about trust [Granger S. 2001]; therefore, to attain a high level of security attention must also be given to QA, which in turn affects security aspects and influences SbD. A Thorough QA program in which encompasses all aspects of QA are investigated has the potential to reduce security vulnerabilities and deficiencies.

below we present the list of QA requirements.

1. Any manufacturer or organization that supplies SW or HW components to an organization that is in the energy sector ecosystem, should adopt QA and quality management standards such as the ISO/IEC 250* stack of standards related to QA, e.g., ISO/IEC 25022:2016, ISO/IEC 25023:2016, ISO/IEC 25030:2019, ISO/IEC 25065:2019, or any other standard that supersedes them.

The table below presents the quality requirements stated in ISO/IEC 25010.

Functional Suitability	Reliability
Functional completeness	Maturity
Functional correctness	Availability
Functional appropriateness	Fault tolerance
Performance Efficiency	Recoverability
Time behavior	Security
Resource utilization	Confidentiality
Capacity	Integrity
Compatibility	Non-repudiation
Coexistence	Accountability
Interoperability	Authenticity
Usability	Maintainability

Appropriateness recognizability	Modularity
Learnability	Reusability
Operability	Analyzability
User error protection	Modifiability
User interface aesthetics	Testability
Accessibility	Portability
	Adaptability
	Insatiability
	Replaceability

NOTES

1. Several of the quality requirements that appear in ISO/IEC 250* stack of standards are related to security, e.g., availability, accountability, and authenticity.
2. The requirements are non-functional requirements. Consequently, there is a need to translate them into functional requirements in order to realize them.
3. In the literature the terms dependability, trustworthiness, and survivability are used interchangeably to describe SW security properties [Kahtan 2014]. Therefore, it is understandable that when an organization declares that its systems are secure it is also trustworthy and capable of withstanding cyber attacks.
4. ISO/IEC 25010 defines safety as “freedom from risk.”

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5.3.1.3 Identification and Authentication

Identification and authentication technologies are discussed in standards and BPs. Thus, we will not discuss them in this document. Please refer to Sections 4.4.1, 4.4.2, and 4.5 for our identification and authentication requirements.

5.3.1.4 Access Control

Access control technologies are discussed in standards and BPs. Thus, we will not discuss them in this document. Please refer to Sections 4.4.1, and 4.4.2 for our access control requirements.

5.3.1.5 Logs/Historian

An organization should comply with the requirements outlined in NIST special publication 800-92 “Guide to Computer Security Log Management” or any other standard that replaces it.

The following points should be emphasized.

1. Transactions and activities in the IT and OT environments should be logged. This information should include but is not limited to:
 - a. Time and date to the millisecond.
 - b. A unique identification of the transaction, and event.
 - c. A unique identification of the device, and user.
 - d. Source and target addresses of devices. This implies that the address and identification are unique within the organization.
 - e. Any other information that should enable forensic activities to be conducted.
2. Logs should be protected from malicious activities, such as deletion and record modification.
3. The log records should be sent to a central point for analysis, i.e., the SIEM/SOC.
4. The data fields written in the log should be parameterized.
5. Log parameters should only be changed by an authorized user, i.e., an administrator, whose activities should also be logged.

5.3.1.6 Audit

Auditing is another layer of security controls to protect the organization's assets, and network. Thus, we include this activity as a must for realizing the goal SbD.

The following points should be emphasized.

1. Audit activities can be divided into two major categories.
 - a. The first category consists of a methodical inspection, examination, and evaluation of an organization's ICS (OT, IT, and communication), infrastructure, policies, operations etc. This type of audit is performed by professional auditors performing timely audits. Such audits usually include:
 - An ongoing audit of the entire ICS environment (OT, IT). Such an audit should cover on an annual basis the entire ICS environment.
 - Penetration tests and other non-destructive security audit activities should be performed quarterly or after a major change in the ICS environment (OT and IT) has been made.
 - b. The second category consists of near real-time audits on the activities of all components and system logs/historians, which are performed by aggregating all logs (e.g., OT, IT, hardware, and communication logs, including software and system logs), scanning the combined logs, and analyzing them to identify abnormal activity. Please note that this type of auditing is highly dependent on the organization's visibility requirements.
2. All audit reports from clause 1, should be distributed to the organization's top management, directorate, CISO, and other individuals responsible for the system.

5.3.1.7 Testing and Validation

Security testing and validation of HW and SW takes on different forms during different phases of the artifact lifecycle (e.g., verify secure coding during the coding phase, and conduct security penetration tests before and after installation in production environment), and as such, it suggests additional security controls to protect the

organization's assets. With in the requirement phase of the lifecycle the following points should be emphasized.

1. Testing must be comprehensive and include both security tests and non-security tests.
2. A thorough understanding of (1) how security tests should be performed, (2) assessing the required time of testing, what are the required testers' expertise, what is the best test environment, etc.
3. The non-security tests (e.g., sanity tests), should be performed from a security perspective, i.e., the ability to subvert the system (e.g., entering illegal values into data fields).
4. Documentation of all tests and their results should be published and disseminated to relevant IT and OT organizational units.

5.3.1.8 Security

This section deals with security requirements, which usually can be gathered from NIST, IEC standards, BPs, etc. In this section, we highlight some general aspects pertaining to security requirements.

1. Identify as many security requirements as possible.

The organization can accomplish this by obtaining expert knowledge, gathering external information, and using techniques such as brainstorming, etc.

2. Translate non-functional requirements.

It may happen that some requirements identified in clause 1 are a high-level security requirement (e.g., confidentiality, non-repudiation, integrity). Such requirements are viewed as non-functional requirements, and organizations might assume they are trivial and therefore neglect them, a situation which is unacceptable. Because these requirements are fundamental, they should be translated into functional requirements and included in the requirement list. For example, Integrity, which is a non-functional requirement, is typically translated into access control, non-repudiation, physical protection, attack detection, etc.; each of those translations

should be further developed to a more technical level, e.g., access control can be developed to specific mechanisms such as biometrics, passwords, etc.

3. Develop mutual understanding.

Foster mutual understanding of the security requirements between security experts and the project team. This effort should enable a common understanding of the security requirements among all project participants.

4. Prioritize the security requirements.

- a. Once the list of security requirements is complete, it is imperative for the organization to prioritize them with respect to aspects such as what should be done, the timeline, verification, and testing methods, etc. This should be included in the KB (see clause 5.3.1.1).
- b. If applicable Include aspects related to identification, authentication, authorization, and privacy.

5. Awareness

Within an organization, there is often a wide range of security awareness among users, and this can affect the ability to adopt the SbD approach. Therefore, users' lack of security awareness must be addressed.

6. Dependencies

- a. Increase understanding regarding the interdependencies between security requirements.
- b. Establish a testing methodology to assess those dependencies and evaluate how they are to be tested (see clause 5.3.1.7).

7. Changes

A change in any requirement (e.g., a change in an application, infrastructure, security requirement) requires that risk assessment and analysis be performed to ensure coherence, coverage, etc.

8. Documentation and KB

- a. Document all security requirements, possible tests, and validation processes applicable to each requirement and the system. Documentation should include all of the building blocks relevant to each requirement.

- b. Develop a repository/KB that contains all of the information related to security requirements and continuously update the repository/KB during all phases of development and maintenance.

5.3.1.9 Other Subjects Related to the Requirement Phase

There are numerous standards and best practices that address topics such as remote access communication, segregation of duties, segmentation, perimeter security, backup and recovery, physical security, law, and regulations. Therefore, it is unnecessary to discuss those aspects of the requirement phase in this document.

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5.4 Design Phase

Usually, the security requirements agreed upon by the organization serve as the input to the design phase. As previously mentioned, we **do not** aim to change the lifecycle of SW development, HW development, system development, or the process of purchasing of any of. We do, however, raise some points concerning cyber security issues. We are confident that adopting this perspective will contribute to a higher level of cyber security and robustness against cyber attacks.

During the design phase the designers/ architects:

- a. Develop the technical details of the artifact, ensuring all details comply with the requirements.
- b. Identify nonconformances or vulnerabilities that were not identified during the requirement phase.
- c. In the case of a purchased product, determine how the product will be integrated into the organizational systems.
- d. Determine how to mitigate security risks.

In the remainder of this section, we address some of the security issues that require emphasis. Other security issues are discussed in the literature (e.g., BPs, standards, academic and non-academic papers).

5.4.1 General Security Aspects Related to the Design Phase.

1. The organization's designers and security experts should analyze all aspects of security pertaining to the project and discuss them.
2. The organization should ensure that its designers possess security awareness and receive relevant training.
3. If the organization's security experts lack the required knowledge and training, the organization should hire a third party that has the relevant security knowledge.
4. A safeguard design should be approved by the CISO before progressing to the next phase of the lifecycle.

5. The designers and security experts should develop and check for possible abuse cases and develop countermeasures against them. Please note that this process may result in the modification of existing security requirements or the addition of new requirements.
6. Design review
 - a. A process of review and verification should take place at the end of the design phase to uncover security flows, e.g., inadequate methods for raising alarms when malicious behavior is detected or a lack of encryption between two components.
 - b. This process must be comprehensive and meticulously performed. At the end of the process, the designers, project managers, QA and security experts, and CISO should be confident that the design provides the highest level of security possible.
7. In this stage, decisions should be made regarding cryptographic protocols, standards, services, security frameworks, security mechanisms, etc.
8. Error handling mechanisms should be designed.
 - a. Security mechanisms should be capable of functioning both during normal operation and when there are failures (see Section 4.4).
 - b. To ensure the security of the system, security aspects should be considered in the design and implementation of all components of the system, including HW and SW. Therefore, the designers and security experts need to:
 - Identify as many failure scenarios as possible during the design phase.
 - Ensure that full visibility is enabled in error situations.
 - Establish a response mechanism to resolve each potential failure scenario.
 - c. In the event of failure, an error handling mechanism should take over.
 - d. The error handling mechanism is responsible for responding to and recovery from errors in SW applications, HW components, infrastructure, and communication systems.
 - e. A well-designed ICS system (OT and IT) should be capable of predicting possible failures and errors, detecting and identifying failure, and initiating remediation activities.

9. All activities and artifacts from the design phase should be documented clearly and incorporated into the KB.

5.4.2 Other Security Related Activities in the Design Phase

This section deals with security related activities not emphasized above.

5.4.2.1 Enhanced Threat Modeling

Enhanced threat modeling enables us to identify various security threats, such as a malicious insider capable of changing a sensor's output.

1. After development of the basic threat model during the requirement phase, the designers must increase their understanding of the security aspects pertaining to the artifact's design, including any previously uncovered security issues, possible vulnerabilities, and attack vectors.
2. In addition, designers should review the risk assessment and threat modeling (see clauses 4.4.12, 5.3.1.1). A key reason for this is to ensure that requirements dependencies are examined.

5.4.2.2 Check and Recheck the Security Design Principles

Complying with security requirements involves activities such as:

1. Ensuring that all security requirements are resolved during the design phase.
2. Verifying that each non-security requirement (e.g., application requirements, infrastructure requirements) does not violate the security architecture (see section 4.5), creates any vulnerabilities, etc.
3. Determining the following:
 - a. Whether the security controls are aligned with standards, and BPs.
 - b. Whether SW applications, HW, systems, etc. (both developed and purchased) are aligned with standards, and BPs.
 - c. Moreover, you should be able to ensure the ability to check and test the security measures developed or purchased. For example, ensure there is

an appropriate test to check if saved passwords are encrypted, hashed, or are saved in plain text.

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5.5 Development Phase

The purpose of this phase is to collect the outcomes from the previous phases (i.e., the requirements and design phases) and implement them as code.

With respect to purchased products, we assume there will be some coding required in the integration of the product into the system (e.g., implementing visibility functions, integrating the product's log/historian into the ICS systems).

With respect to coding, we include products for levels 0 - 2 of the Purdue model for the following reasons:

- a. Those levels may be populated with IoT/IIoT devices that run code.
- b. Regardless as to whether an analog sensor is used in level 0, it is connected, for example, to a PLC or an IoT/IIoT device that runs code.
- c. Firmware is to be considered to be SW.

Therefore, the coding language in a PLC or firmware should still be viewed as a SW language.

Regarding the IT part of an ICS, it is obvious that coding will need to be performed.

In this section, we do not address secure coding techniques, as this topic has been covered in numerous BPs, books, and papers. Moreover, as mentioned in previous sections.

We do not aim to change the lifecycle of SW or HW development, system development, or the process of purchasing of any of. We do, however, raise some points concerning cyber security issues. We are confident that adopting this perspective will contribute to a higher level of cyber security and robustness against cyber attacks.

5.5.1 Secure Coding

The organization should use program language that supports the capabilities of secure coding.

To the best of our knowledge, currently there are no BPs or standards for secure coding in the current programming languages used in PLCs and firmware. Therefore, we encourage

industry to develop some new programming languages that will both have secure coding capabilities and support high availability. Alternatively, it may be necessary to use modern devices (e.g., IoT/ IIoT devices) that support programming languages and enable secure coding.

In this section, we don't aim to tell coding experts how to code. Rather we present the following guidelines for integrating SbD and security features in coding practice:

1. Code should be developed in accordance with requirements and specifications (e.g., design specifications). Discrepancies should be resolved without neglecting requirements, mechanisms, and considerations of SbD and cyber security.
2. Developers should pay particular attention to the aspects of security related to coding, such as secure coding, connection among modules, etc.
3. When developing, developers should pay particular attention to testability, i.e., how the artifact (e.g., program) or purchased product is to be tested.
4. Comprehensive testing of a unit (i.e., the smallest piece of code that can be logically isolated in a system; see smartbear.com) should include both non-security and security tests.
5. Version management and control tools should be used to transfer artifacts between one environment and another (e.g., from the development environment to the test environment). This also pertains to SW purchased for the IT environment and level 3 of the Purdue model.
6. The transfer of code between environments should be approved by the project's management team, CISO, and the person responsible for the receiving environment (i.e., the test environment).

Notes:

- We are well aware of the fact that there are coding languages in the OT environment that do not have secure code language or mechanisms. When such coding languages are used, rigorous testing should be performed.
- HW components used in levels 0-3 of the Purdue model that will operate in an unprotected environment (e.g., outdoors) should be electromagnetically protected.

5.5.2 Code Review

Code review is considered as a QA tool. However, the process can also be used to identify vulnerabilities and security bugs. Code reviews can be performed manually or automatically; these two methods are complementary and should be used together.

5.5.2.1 Manual Code Review

The benefits of manual code review include the ability to:

1. Find vulnerabilities (e.g., a part of the code that is not being used or a part of the code which, when used, will cause a vulnerability).
2. Identify components that are not defined or used properly (e.g., a protocol that is used incorrectly).
3. Identify complex code that can be replaced with a simple alternative.
4. Identify misinterpretations of the design (e.g., the requirement phase requires 2FA, however due to a glitch, users may be able to use 1FA in some cases).
5. Identify undesirable flows in the implementation logic and workflow.
6. Identify deficiencies and vulnerabilities in earlier phases (e.g., a function that was not assigned a security level in the design phase).
7. Analyze the flow of data among components.

5.5.2.2 Automated Code Review

The benefits of automated code review include the ability to:

1. Saves time and effort.
2. Using it can be automated and integrated into developers' workflows.

5.5.2.3 Integration of code review

This section deals with what is expected from the organization regarding code review.

1. As part of its code verification process, manual and automated, the organization should use formal code verification tools.
2. An automatic code review tool should be able to analyze the code both static and review.
3. Static and dynamic code review should be performed in the development and testing phases.
4. Dynamic code review should be incorporated into the regular audit and security testing (see Sections 4.4.12, 5.5.3, and 5.3.7) for the purpose of identifying unauthorized modification of code.

5.5.3 Testing

It is not our aim to explain how the test experts should perform their activities and what methodology they should use. However, we do wish to emphasize some aspects of testing in order to enhance cyber security.

1. Our assumption is that testing will be performed by testing experts, such as employees or third parties specializing in OT, IT, and communication system testing.
2. Applications, operating systems, HW, communication, and security testing experts should be familiar with the standards, BPs, and all relevant information pertaining to their area of expertise.
3. Testing experts should be provided with the organization's requirement documents (including design documents), the results of unit and integration tests, and the results of code analysis.
4. The testing process, including the test scenarios and results, should be documented.
5. Testing information (e.g., testing scenarios, method, and results), should be available to the project's designers, coding experts, test experts, and CISO.
6. The organization should set up a testing environment that encompasses and integrates its OT, IT, and communication environments. The testing environment should be as similar to the production environment as possible.

7. The testing environment should be isolated from the outside world, e.g., the Internet.
8. A special test environment should be set up for tests which require connection to the outside world (e.g., the Internet, business partners). The test environment should also be isolated from organizational networks, and it should be protected similar to the manner in which the production environment is protected.
9. The security tests will include the following:
 - a. Penetration tests
 - b. Robustness tests
 - c. Fuzz tests
 - d. Denial-of-service tests (DoS)/distributed denial-of-service attacks (DDoS)
 - e. Error handling tests
 - f. Data protection tests
 - g. Other testing scenarios in which an attempt to penetrate the system is made, with the aim of identifying the system's vulnerabilities.
10. When all artifact discrepancies have been corrected and no vulnerabilities have been discovered for over a week of meticulous testing efforts, the testing will be considered complete, and certified as such by the project manager, CISO, and person responsible for testing.

5.5.4 Deployment in the Production Environment

1. There are three steps in the process of deploying the artifact in the production environment.
 - a. In the first step, the SW, HW, and system are deployed in a pre-production environment. This will allow a series of cyber security tests (described in Section 5.5.3) to be performed on the artifact in an environment that is as close to the production environment as possible.
 - b. In the second step, the SW, HW, and system are deployed in the production environment.

- c. As soon as the artifacts have been deployed in the production environment penetration testing, as well as other security tests, should be performed.
2. The project manager, CISO, and the person responsible for testing are responsible for declaring that the artifact can be transferred to the production environment.
3. All SW deployment should be performed through the version management and control system.

5.5.5 General Recommendations Related to Testing

1. The energy sector ecosystem should establish an independent testing institute responsible for performing security testing and evaluating all COTS HW and SW used by organizations in the sector.
2. Throughout the ecosystem, all test documentation and evaluations should be made public.
3. Moreover, every organization should conduct its own security tests on the same COTS HW and SW, on its architecture and its environment.

5.6 Maintenance

This section deals with maintenance activities. We only consider computerized components in the ICS environment (e.g., IoT devices, servers, software application, PLC, sensors containing CPU and memory). It is not our intent in this document to cover all of the required maintenance activities, however we describe a few activities that are considered important for preserving aspects of SbD.

Additionally, in this section we do not dictate how an organization's maintenance experts should perform their activities and what methodologies they should use. However, we must emphasize that the organization should **ensure that any maintenance activity does not endanger or harm the cyber security protection mechanisms in place.**

The maintenance activity also includes replacement activities.

At a minimum, the person responsible should perform the following cybersecurity related activities:

1. Preprocessing activities
 - a. Ensure that the components undergoing maintenance have been tested according to organizational policies and procedures, e.g., in a testing environment, a near-production environment.
 - b. A fallback mechanism is available and has been tested in a near- production environment.
2. Postprocessing activities
 - a. Conduct a cyber security test in the production environment.
 - b. Coordinate with the various organizational entities responsible for ensuring the success of the maintenance activity (e.g., validation of outcomes).

5.7 Disposal

The subject of IT component disposal is addressed in international standards such as NIST.SP 800-88, 800-53 Reversion 5 and 800-171 Revision 2, and more. Therefore, we do not elaborate further on this topic.

All we would like to add is the requirement to impose those standards requirements on all devices installed at Purdue model levels 0 – 2.

6 Conclusions and Future Work

This work presents the requirements for implementing the SbD concept in ICS, especially in the energy sector. The fundamental reasoning for this work is the assumption that the OT part of the ICS is heading toward digitalizing its components, such as sensors, actuators, PLCs, etc. Thus, with the necessary modifications, we need to implement cybersecurity concepts and aspects in the OT environment, as we already implement them in the IT environment. Furthermore, as we begin such a transition, it's natural to implement cybersecurity concepts and aspects via the SbD framework.

Within the suggested framework, we strongly recommend setting up an ecosystem for all participants related to the energy sector. Such an ecosystem will have the authority and ability to enforce cybersecurity requirements and promote and lead continuous improvement processes in cybersecurity issues.

The paper is divided into two parts. The first describes non-technical requirements, such as the management role. The second part describes the technical aspects, alongside the software development life cycle.

Further research is required to build SbD processes within the HW lifecycle process, the combination of HW and SW implemented within the firmware, and the supply chain processes.

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Appendix A - List of Acronyms

AES	Advanced encryption standard
BP	Best practice
CERT	Cyber emergency response team
CISO	Chief information security officer
COBIT	Control objectives for information and related technologies
COTS	commercial off-the-shelf
CPU	Central processing unit
DES	Data encryption standard
DLP	Data leakage prevention
DMZ	Demilitarized zone
DNP3	Distributed Network Protocol 3
DDoS	Distributed denial-of-service
DoS	Denial-of-service

ECC	Elliptic curve cryptography
EPROM	Erasable programming read-only memory
HMI	Human-machine interface
HW	Hardware
ICS	Industrial control systems
IDPS	Intrusion detection prevention system
IoT	Internet of things
IIoT	Industrial Internet of things
IT	Information technology
KB	Knowledge base
MFA	Multi-factor authentication
MTD	Moving target defense
NMS	Network management/ monitoring system
OTP	One-time password
OT	Operational technology
PLC	Programmable logic control
QA	Quality assurance
RAM	Random access memory
RBAC	Role-based access control
ROM	Read-only memory
RSA	Rivest-Shamir-Adelman encryption method
SbD	Security by design
SDLC	Software development lifecycle
SIEM/SOC	Security incident and event management and security operations center
SIEM	Security incident and event management
SOC	Security operations center
SW	Software
TPM	Trusted platform module
UML	Unified modeling language

ZT	Zero trust
1FA	One-factor authentication
2FA	Two-factor authentication

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